Passive bottom loss estimation using compact arrays and autonomous underwater vehicles

Martin Siderius, Lanfranco Muzi, and Elizabeth Thorp Küsel
Portland State University
Electrical and Computer Engineering Department
1900 SW 4th Ave., Portland, OR 97201
Phone:(503) 725-3223 fax:(503) 725-3807 Email: siderius@pdx.edu

Award Number:
http://www.ece.pdx.edu/Faculty/Siderius.php

LONG TERM GOALS

The goal of this research is to design new processing techniques for studying the ocean ambient-noise field, for the purpose of environmental characterization and SONAR-system performance prediction. This is specifically considering sensing from underwater vehicles.

OBJECTIVES

Use of available databases has been proven to be inadequate for SONAR performance prediction in littoral waters, the main source of error being the low accuracy in bottom-loss estimation [Ferla, 2002]. While the classical approach to acquiring the bottom reflection coefficient as a function of frequency and grazing angle involves the use of an active acoustic source and a line array of hydrophones, this estimate can also be obtained passively by beamforming the naturally occurring marine ambient-noise acoustic field recorded by a vertical line array [Harrison, 2002].

By eliminating the need for artificial acoustic sources, the technique achieves several benefits, among which reduced environmental impact and counter-detection risk, but also reduced equipment complexity, cost, weight, and power consumption. These features, together with the recent advances in the technology of autonomous underwater vehicles (AUV), make it now possible to envision an efficient, cost effective survey tool for seabed characterization composed of a short array mounted on an AUV.

While AUV mounting would require arrays of length presumably below 2m, the passive technique has proven effective in the frequency range 500–5000Hz when employing arrays of lengths between a few meters to several tens of meters. For the frequency range

indicated above, the poor angular resolution of the short arrays required in AUV deployment causes an underestimation of the loss and poor resolution of its grazing angle dependent features [Harrison, 2008]. The research work described in this report focuses on processing techniques for improving the performance in reflection-loss estimation of arrays whose length is such that they can be mounted on an AUV.

APPROACH

We have fully developed the theoretical framework and thoroughly documented the application of a technique ("High resolution bottom-loss estimation", HR-BL) that enhances the angular resolution of the BL estimated from array data, by exploiting specific properties of the ambient-noise vertical coherence function to remove some inherent limitations of conventional beamforming [Publication #2] [Siderius, 2013]. We later proposed a technique (hereafter referred to as "frequency based extension", FBE) that uses data measured at different frequencies by the physical hydrophones, to approximate the coherence function at the location of the sensors of a longer array. In a preliminary empirical study on both simulated and measured data, this approach showed potential for recovering an appreciable amount of the information lost by a shorter array. In the second phase of this study, we have investigated the reason for its success, and perfected its application in conjunction with HR-BL [Publication #1].

In this section, we first describe the FBE algorithm, and then briefly motivate its use with theoretical and empirical arguments. In FBE the coherence function $C_{\omega_0}(z)$ between two sensors at spacing z, in an array of length l at frequency ω_0, is reconstructed, starting from an estimate $\hat{C}_{\omega_0}(z)$ obtained from measurements on an array of length $l_0 < l$, by using the coherence function at a higher frequency ω_1 and spacing $z_0 \le l_0$ as an estimate of the function at frequency $\omega_0 < \omega_1$ and spacing $z_1 > l_0$, with the condition:

$$\omega_1 z_0 = \omega_0 z_1, \tag{1}$$

or, equivalently, $z_0/\lambda_1 = z_1/\lambda_0$.

It is easier to start discussing the algorithm for a bottom that has constant physical properties (hereafter referred to as "halfspace"), in which case the bottom reflection coefficient is independent of frequency. The theoretical starting point is provided by the integral expression derived by Harrison [Harrison, 1996] for the *unnormalized* noise vertical coherence:

$$C_\omega(z)=\int_0^{\pi/2}\frac{2\pi\,(c_r/c_s)\sin\theta\cos\theta}{1-R_s(\theta)\,R(\theta)\,e^{-as_c(\theta)}}$$
$$\left\{e^{i(\omega/c)z\sin\theta}e^{-as_p}+R(\theta)\,e^{-i(\omega/c)z\sin\theta}e^{-a\left[s_c(\theta)-s_p(\theta)\right]}\right\}d\theta. \tag{2}$$

In Eq.(1), $\theta\equiv|\theta_r|$ is the absolute value of the angle of incidence of the wave on the sensors, s_c and s_p are the complete and partial ray-path lengths, whose dependence on θ is determined by the sound-speed profile in the water column, and R and R_s are the bottom and surface power reflection coefficients. In general, besides the ray angle, the reflection coefficients are also a function of frequency, but for the sake of simplicity this dependence will not be indicated explicitly. Note that a is the power attenuation per unit length along the ray path.

Since the reflection coefficient of a halfspace bottom is independent of frequency, if one neglects the frequency dependence of a (an acceptable assumption, as shown later), the integrand of $C_\omega(z)$ depends only on the product ωz, or, equivalently, the z/λ ratio. As an example, the normalized coherence function $C'_\omega(z/\lambda)$ [computed dividing the value given by Eq.(2) by the square root of the product of the power spectral densities measured at ω for the two hydrophones] is plotted in Figure 1 for a halfspace having $c=1565\,\mathrm{m/s}$, density $\rho=1500\,\mathrm{kg/m^3}$, and compressional attenuation $\alpha_c=0.2\,\mathrm{dB}/\lambda$. As expected, the coherence function is largely frequency independent, except for the amplitude variations due to the inclusion of a in Eq.(2). This indicates that FBE in this case would yield a very good approximation of the coherence function of a longer array starting from the data provided by a shorter array, especially for $z/\lambda\geq 4$.

For example, using Figure 1 for reference, at $f_0=1\mathrm{kHz}$ the maximum spacing for a 10-element array is $z_0=1.35\mathrm{m}$. An additional ("nonphysical") sensor number 11 would be at $z_1=1.5\mathrm{m}$ from sensor number 1, which, by Eq.(1), yields $f_1=(10/9)f_0=1.111\mathrm{kHz}$. The point corresponding to $z/\lambda=1$ on the 1.111kHz curve is then used for the "nonphysical" sensor number 11 on the 1kHz curve. The maximum available value for z_0 is chosen on purpose in this example, so as to minimize the difference between ω_0 and ω_1.

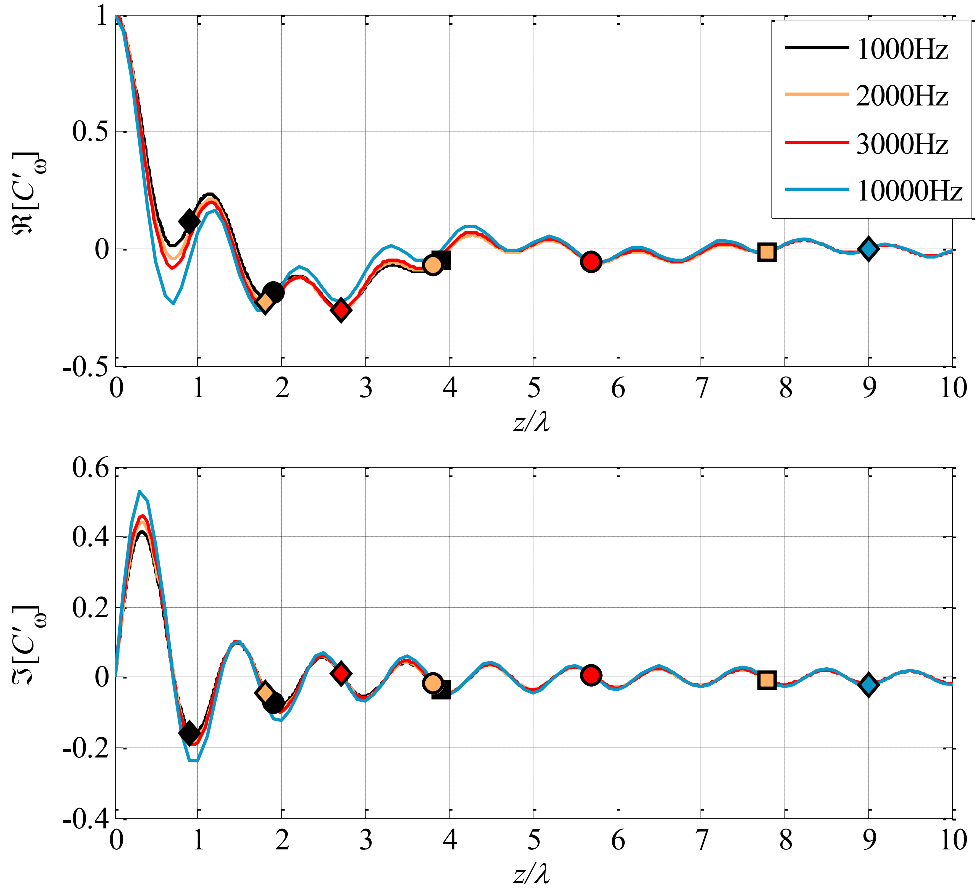

Figure 1: Halfspace bottom: Normalized coherence-function real (top) and imaginary (bottom) part at several frequencies, as a function of the z/λ ***ratio. The markers indicate the positions of sensors number 10 (diamond), 20 (circle), and 40 (square) for an array of spacing*** $d = 0.15\text{m}$. ***Given the quantity on the horizontal axis, at a lower frequency two consecutive points of a curve are closer than they are at a higher frequency, and the curve corresponding to a higher frequency reaches higher values on the horizontal axis. Note the almost perfect overlap of the curves.***

Although the treatment above relies on the fact that the bottom reflection coefficient is independent of frequency, we have verified empirically that use of the FBE algorithm prior to BL estimation improves the quality of the results also in the case of layered bottoms, where the frequency dependence of the reflection coefficient can be dramatic. The reason for this is not immediately apparent from theoretical models, which present $C_\omega(z)$ in integral form [e.g., Eq.(2)], or as a series expansion [Cox 1973]. Its expression as the combination of a direct and an inverse Fourier transform between the hydrophone-spacing z and the vertical wavenumber k domains makes the connection between z and ω explicit [Publications #1 and #1], but this fact alone does not fully explain why FBE is so effective in aiding BL estimation.

The first step in justifying the use of FBE on layered bottoms is based on the fact that, if some simplifying hypotheses are made (isospeed water column, negligible volume attenuation, unit reflection coefficient for the sea surface), one can show that *the imaginary part of the coherence function is independent of the bottom reflection properties*: The bottom reflection information is predominantly contained in the real part. However, observation of the real part suggests that, even for layered bottoms, the $C'_{\omega}(z/\lambda)$ curves vary rather smoothly with frequency: If one considers two $\mathrm{Re}\, C'_{\omega}[(z/\lambda)]$ curves at "close" values of ω, their values at the same z/λ will be "close" too. When this *smooth variation of the coherence with frequency* is assumed, FBE can be applied to layered bottoms, and we have verified over a significant number of cases, using both simulated data — produced by an implementation of Eq.(2) and by OASN [Schmidt, 2004] — and measured data, that the hypothesis holds, and the algorithm does improve the bottom-loss estimate from short arrays.

FBE is particularly suited for the limited power and computational resources of an AUV payload, because it is computationally simple, and makes a more efficient use of the frequency band available to modern acquisition systems, which often extends well beyond the array design frequency. It is important to stress that, as one can expect from the theoretical treatment, in order for these techniques to work, the data should be produced by natural surface noise only.

WORK COMPLETED

FBE has been fully theoretically justified for frequency independent bottoms, and an explanation based on both theoretical and empirical arguments has been proposed for its use for bottom-loss estimation for layered bottoms too. The algorithm has been applied to numerous cases using both data simulated by OASN and Eq.(2), and measured data, assessing the validity of its application also in conjunction with the HR-BL algorithm.

The NEAR Lab has also participated in the "*Glider sensors and payloads for tactical characterization of the environment 2015*" (GLISTEN15) sea trial, carried out August 26th – September 9th, 2015 in the Capraia Basin, Tyrrhenian Sea, Italy. The area has been relatively well characterized in the past by several experiments, and Figure 1 shows the experimental area (red polygon) along with the two major propagation tracks (yellow lines), a range dependent track running North-South, and a range independent track running approximately East-West.

Figure 1: Capraia basin with experimental area delimited by the red polygon. Yellow tracks correspond to ship track, with deployment points for moored instruments.

The experiment was carried out with the aid of the Research Vessel *Alliance*, and included the test a Slocum glider equipped with a prototype hydrophone line array (PHA) for bottom characterization using ambient noise. Moorings with PHA and HYDRA data acquisition system as well as SLIVA were also deployed to serve as comparison to data sets recorded by the glider. Furthermore, an original, low cost prototype acoustic equipment for detection of marine mammals was tested.

RESULTS

As an example of the application of FBE to simulated data generated by a layered bottom, Figure 1 shows the predicted [Jensen, 2011] and estimated bottom loss, for the bottom type described in TABLE I, comparing the results of the conventional beamformer used in Harrison and Simons' original technique to those of the combined FBE+HR-BL processor. Note that none of these techniques should be expected to recover completely the very fine structure observed in the theoretical prediction, since finite-length/finite-spacing arrays are assumed. Water-column and bottom configuration for the

simulated case; Δ is the layer thickness, ρ is the density, α_c is the compressional volume attenuation, and λ is the wavelength.

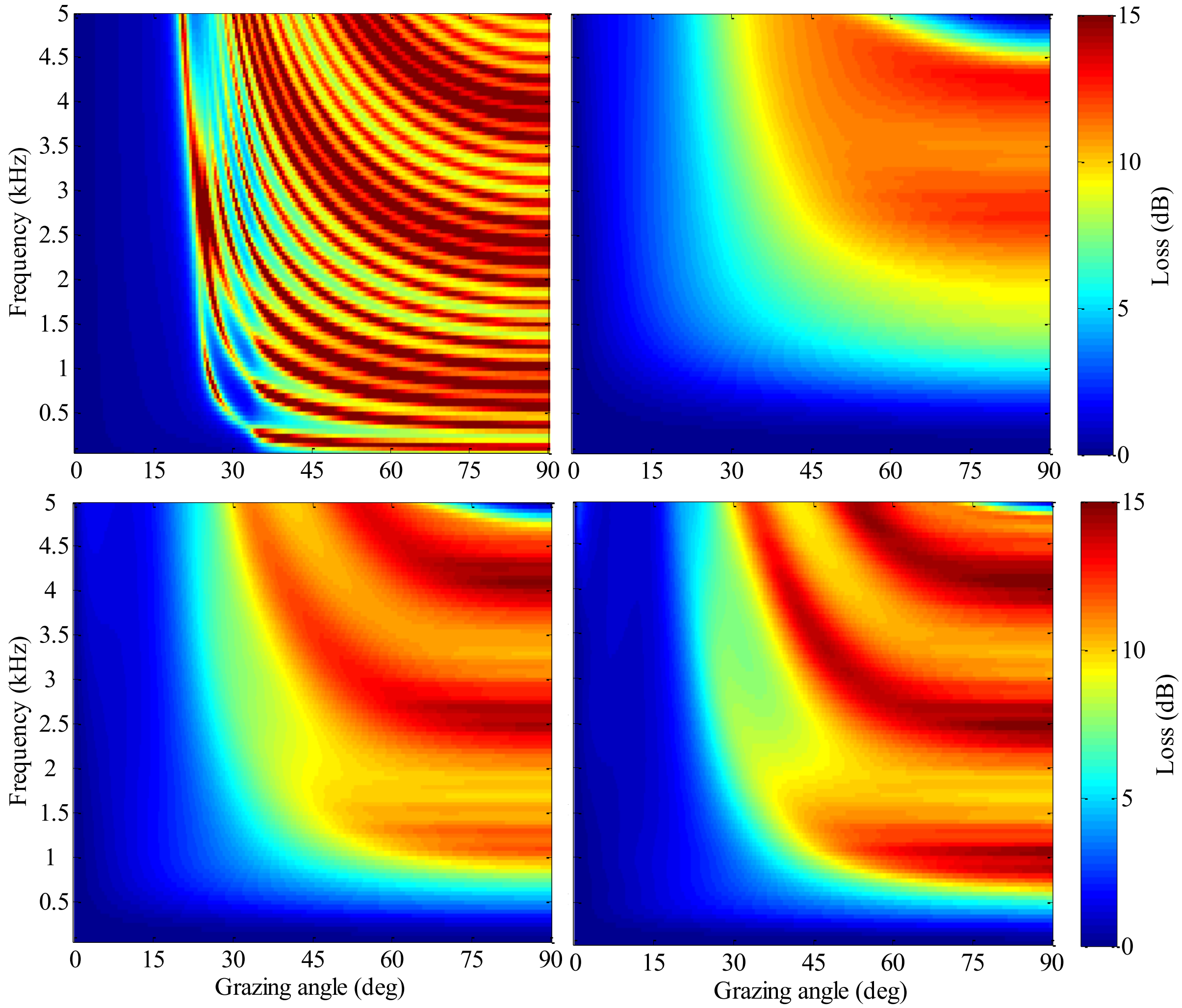

Figure 1: Double layer over halfspace: BL predicted using the reflection coefficient given by Jensen et al.'s model (top left). BL estimated from OASN data using CBF over 12 (top right), and 24 (bottom left) sensors, and BL estimated by HR-BL over 12 sensors extended to 24 by FBE (bottom right).

TABLE I. Water-column and bottom configuration for the simulated case; Δ is the layer thickness, ρ is the density, α_c is the compressional volume attenuation, and λ is the wavelength.

	$\Delta(\mathrm{m})$	$c_p(\mathrm{m/s})$	$\rho(\mathrm{kg/m^3})$	$\alpha_c(\mathrm{dB}/\lambda)$
Water	170	1500	1000	1e-4
Layer #1	0.5	1565	1500	0.2
Layer #2	3	1625	1700	0.3
Halfspace	∞	1800	2000	0.5

As an example of FBE application to measured data, Figure 2 shows the comparison between the bottom loss estimated by the HR-BL algorithm alone, Harrison and Simons' technique, and FBE combined with HR-BL, on data from the Boundary 2003 experiment (see TABLE II — data provided by the NATO-STO Centre for Maritime Research and Experimentation, formerly NATO Undersea Research Centre). Note that, in this case, the low sampling rate does not allow us to carry out the coherence-function extension (from 20 to 32 elements) up to the design frequency of 4166Hz.

TABLE II. Boundary 2003 data: Dataset and array basic features.

Num. of array elements	Spacing (m)	Sampling freq. (Hz)	Design freq. (Hz) @ $c = 1500\mathrm{m/s}$	Deployment type
32	0.18	12000	4166	Drifting

In both the cases presented above, as well as in numerous others analyzed but not shown here for the sake of brevity, the FBE algorithm is capable of recovering information that is lost by the shorter array, even when the bottom is layered.

IMPACT/APPLICATIONS

This work may have a significant impact on several Navy SONAR applications (e.g., ASW, MCM, underwater acoustic communications). Knowing the seabed properties will

improve at-sea situational awareness by being able to accurately predict acoustic propagation. And, because this is a passive method, it can be designed into a system used for covert activities, low power applications (such as AUV deployment), and can be used even in environmentally restricted areas.

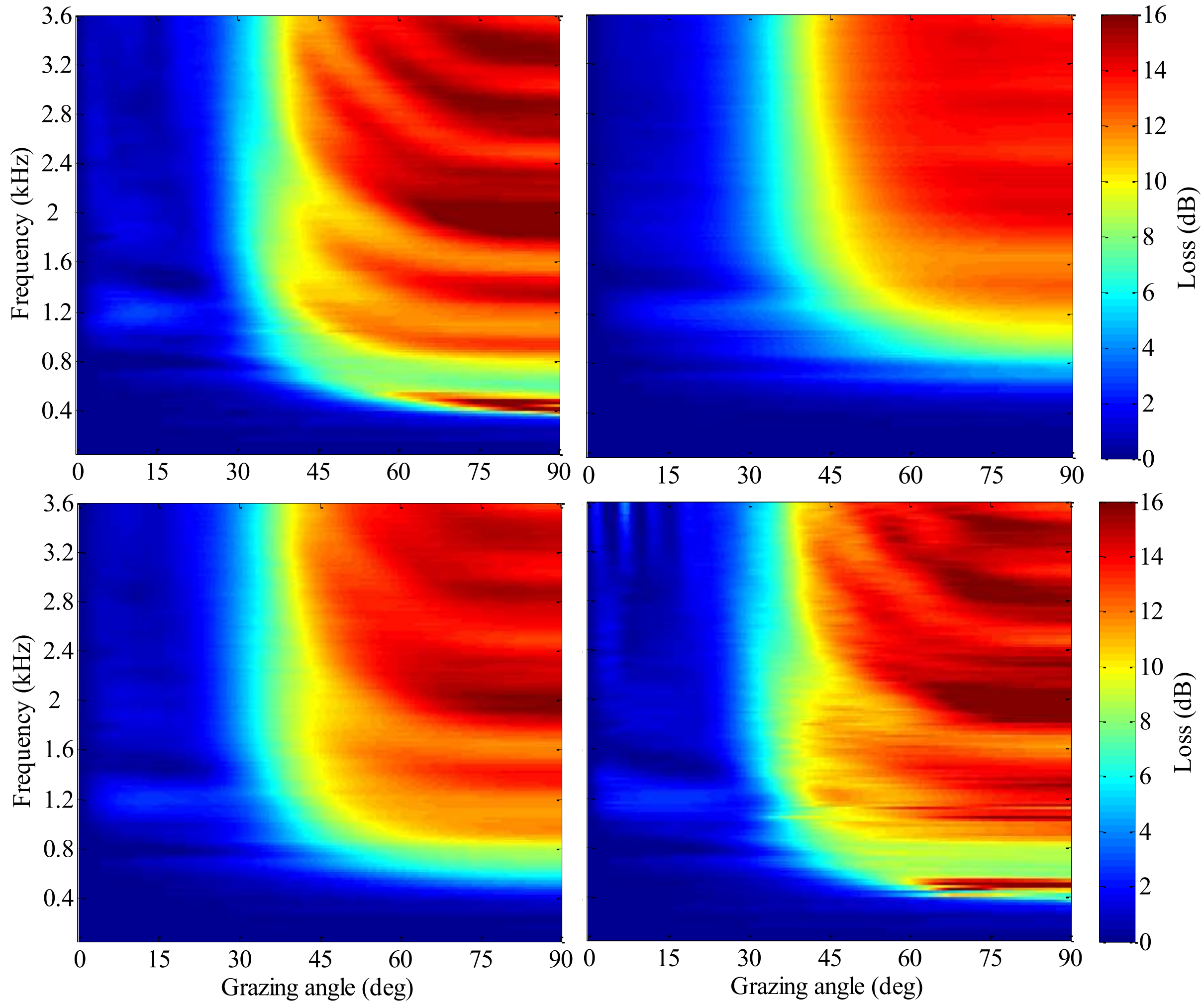

Figure 2: Boundary 2003 MFA data: BL estimated by HR-BL over 32 elements (top left), by CBF over 20 (top right) and 32 elements (bottom left), and by HR-BL after extending the coherence function estimated from 20 sensors to 32 sensors by FBE.

REFERENCES

[Ferla, 2002] C. Ferla and F. B. Jensen, “Are current environmental databases adequate for sonar predictions in shallow water?” *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance*, Eds. N.G. Pace and F. B. Jensen, Kluwer Academic Publishers, 555-562 (2002).

[Harrison, 2002] C. H. Harrison and D. G. Simons, "Geoacoustic inversion of ambient noise: A simple method," *J. Acoust. Soc. Am.* **112**, 1377-1389 (2002).

[Harrison, 2008] C. H. Harrison and M. Siderius, “Bottom profiling by correlating beam-steered noise sequences,” *J. Acoust. Soc. Am.* **123**, 1282–1296 (2008).

[Siderius, 2013] M. Siderius, L. Muzi, C. H. Harrison, and P. L. Nielsen, "Synthetic array processing of ocean ambient noise for higher resolution seabed bottom loss estimation," *J. Acoust. Soc. Am.* **133**, EL149-EL155 (2013).

[Harrison, 1996] C. H. Harrison, "Formulas for ambient noise level and coherence," *J. Acoust. Soc. Am.* **99**, 2055-2066 (1996).

[Cox, 1973] H. Cox, “Spatial correlation in arbitrary noise fields with application to ambient sea noise,” *J. Acoust. Soc. Am.* **54**, 1289-1301 (1973).

[Schmidt, 2004] H. Schmidt, OASES Version 3.1 User Guide and Reference Manual, Massachusetts Institute of Technology, http://acoustics.mit.edu/faculty/henrik/oases.html, Cambridge, MA, (2004).

[Jensen, 2011] F. B. Jensen, W. A. Kuperman, M. B. Porter, and H. Schmidt, “Fundamentals of ocean acoustics,” in *Computational Ocean Acoustics* (Modern Acoustics and Signal Processing), 2nd ed. (Springer, New York, 2011), Chap.1, pp.38-50

PUBLICATIONS

1. L. Muzi, M. Siderius, and P. L. Nielsen, "Frequency based noise coherence-function extension, and application to passive bottom-loss estimation,” *J. Acoust. Soc. Am.* (2015) [Submitted, refereed].
2. L. Muzi, M. Siderius, J. E. Quijano, and S. E. Dosso, “High-resolution bottom-loss estimation using the ambient-noise vertical coherence function”, *J. Acoust. Soc. Am.* **137**, 481–491 (2015) [Refereed].
3. P. L. Nielsen, M. Siderius, and L. Muzi, "Glider-based seabed characterization using natural-made ambient noise,” *Oceans - Genoa, 2015*, [Accepted, IEEE conference proceedings].